EXHIBIT A

Lucent Technologies
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subject: **Adaptive Quality Control Loop (QCL) for Link Adaptation in Packet Data Communications**
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from: **Sridhar Gollamudi**
Dept. 00000
LC 9N-Z00
9999
gollamudi@lucent.com

Pantelis Monogioudis
Dept. 00000
LC 9N-Z00
9999
monogiou@lucent.com

00000-000625-03TM

TECHNICAL MEMORANDUM

Packet communications over shared channels require link rate adaptation and scheduling. The performance of link adaptation is heavily dependent on the thresholds that determine the selection of a Modulation and Coding Scheme (MCS). It is shown that without any threshold control mechanism, link quality metrics such as Bit Error Rate (BER) or Block Error Rate (BLER) as well as average delay due to HARQ retransmissions deteriorate significantly with increasing user mobility. In order to alleviate these effects, a control mechanism that adjusts MCS selection thresholds to suit the communications environment is required. We propose an adaptive threshold control scheme named Quality Control Loop (QCL). QCL stabilizes quality metrics such as BER, BLER and average delay around the desired values that depend on the application Quality of Service (QoS) requirements. The proposed method is similar in nature as well as simplicity of implementation to the quality control loop (Outer Loop Power Control) used for dedicated channels.

1 Introduction

In packet data communications over time-varying wireless channels, rate adaptation is a technique by which the data rate of each transmitted packet is chosen dynamically based on the latest estimate of channel condition. The aim of such a scheme is to maximize the rate of information that can be reliably transmitted for each channel condition. Typically, the rate for a packet is selected from a fixed table of possible rates and is based on the latest available estimate of a channel quality metric such as Signal to Interference Ratio (SIR) or Shannon capacity. Either the final choice of rate or the instantaneous channel quality metric is relayed to the transmitter, usually via a feedback channel.

Different rates are typically implemented by using different channel coding and/or modulation schemes. A Modulation and Coding Scheme (MCS) refers to the combination of modulation scheme and coding scheme used for a particular packet transmission. A channel quality metric estimated at the receiver is compared to different thresholds to determine the MCS with which the next transmission should be transmitted. The thresholds partition the range of possible values taken by the metric to different bins, each corresponding to an MCS selection. The choice of thresholds can significantly affect such link performance criteria as average throughput, packet and bit error rates, and average number of retransmissions with Hybrid-ARQ schemes. Optimal choice of thresholds is a complicated function of several factors such as,

- Metric estimation accuracy
- User mobility (Doppler spread)
- MCS feedback loop delay
- Fading statistics and SIR statistics at the receiver
- Channel profile
- Choice of MCS table
- Transmitter and receiver design

Due to the time-varying nature of many of these factors, adaptive choice of thresholds is more suitable than using fixed thresholds. Furthermore, due to the large number of factors that affect appropriate choice of thresholds, measuring the factors in real-time and using look-up tables to select thresholds may be impractical.

The proposed scheme adaptively selects thresholds that satisfy specific quality requirements, without requiring measurement of the factors that affect their optimal choice and without the need for look-up tables. The proposed algorithm is implemented at the place where thresholds are required, which may be at the receiver if MCS decisions are fed back to the transmitter, or at the transmitter if MCS selection is performed at the transmitter using fed-back estimates of the metric. *The only inputs to the algorithm are the MCS level and CRC result for each packet.*

2 Rate Adaptation and Performance Metrics

In the packet data communications system under consideration, each packet is transmitted with an MCS level selected from a table of MCS levels numbered from 1 through M, in increasing order of data rate. Let the data rates corresponding to the different MCS levels be denoted by $R_1, R_2, , R_M$, respectively. It is assumed that the duration of each transmitted packet is the same. The channel quality metric, denoted by μ, can be assumed, without loss of generality, to be such that a larger metric implies a channel that is capable of a higher data rate. The receiver measures the channel quality metric to obtain a metric estimate, $\hat{\mu}$. Thresholds $\theta_1, \theta_2, , \theta_M$ are defined such that a channel for which the estimate of metric is larger than θ_m is deemed capable of reliably transmitting with an MCS level smaller than or equal to m. Therefore, in order to maximize average transmitted data rate, rate adaptation selects the mth MCS level if $\hat{\mu}$ is between θ_m and θ_{m+1}. If there is a constraint to transmit data in every packet interval, the MCS level 1 may be chosen when the metric estimate is smaller than θ_1. In such a case θ_1 is not required for rate adaptation.

We first consider the performance of the system without HARQ. The effect of HARQ is addressed in Section 3.1. The performance and quality metrics of interest are link throughput (R), block error

rate (P_{BL}) and bit error rate (P_B). The performance and quality metrics of interest are functions of the thresholds, the individual block error rate curves of each MCS with respect to the metric estimate $\hat{\mu}$, and the statistics of $\hat{\mu}$. Let $f_{\hat{\mu}}(\hat{\mu})$ denote the probability density function of the metric estimate $\hat{\mu}$. The probability of choosing the mth MCS can be written as

$$P_m = \int_{\theta_m}^{\theta_{m+1}} f_{\hat{\mu}}(\hat{\mu}) d\hat{\mu}. \tag{1}$$

For the Mth MCS, θ_{M+1} is taken to be infinity. Also, as noted above, if there is a constraint to transmit even when $\hat{\mu} < \theta_1$, then θ_1 can be taken to be negative infinity.

A decision of whether or not a received packet is decoded correctly is made at the receiver using a CRC test. A block error is said to occur if the CRC check fails. Denoting the block error rate of the mth MCS (without MCS adaptation) as a function of the metric estimate $\hat{\mu}$ as $p_m(\hat{\mu})$, the probability of block error conditioned on the mth MCS being selected can be written as

$$p_m = \frac{1}{P_m} \int_{\theta_m}^{\theta_{m+1}} p_m(\hat{\mu}) f_{\hat{\mu}}(\hat{\mu}) d\hat{\mu}. \tag{2}$$

Block error rate with automatic MCS selection is then given by

$$P_{BL} = \sum_{m=1}^{M} p_m P_m. \tag{3}$$

Block error rate is widely used as an indicator of transmission reliability. However, it is not an accurate indicator when adaptive MCS selection is operational, since it penalizes CRC failure of a packet with a larger number of bits with the same weight as a failure of a packet with a smaller number of bits. Since failure of a larger packet is more damaging to transmission quality, bit error rate is a more appropriate quality metric. We assume that all bits of a packet with a failed CRC check are considered to be in error while all bits of a packet with a successful CRC are considered correctly decoded. BER can then be defined as

$$\begin{aligned} P_B &= \frac{E\{\text{Number of bit errors per second}\}}{E\{\text{Number of transmitted bits per second}\}} && (4) \\ &= \frac{\sum_{m=1}^{M} R_m p_m P_m}{\sum_{m=1}^{M} R_m P_m}, && (5) \end{aligned}$$

where R_m is the rate or number of transmitted bits per second with the mth MCS.

Remark: With the above definition, BER is identical to BLER if the transmitted rate does not change with time.

Link throughput, defined as the number of correctly decoded bits per second, can be expressed as

$$R = \sum_{m=1}^{M} R_m (1 - p_m) P_m. \tag{6}$$

Remark: In a scheduled environment, all statistics defined above, such as the density function of metric estimate $f_{\hat{\mu}}(\hat{\mu})$, MCS probabilities P_n, MCS error rates p_n, BLER, BER and throughput R, are conditioned on the user of interest being scheduled.

3 Quality Control Loop

A rate adaptation scheme is completely specified by the choice of thresholds, $\theta_1, \theta_2, \cdots, \theta_M$. The thresholds should ideally be chosen to maximize throughput R subject to an upper bound on either BLER or BER. However, an analytical or adaptive solution to this problem is quite complicated. Furthermore, as seen from the results in Section 4, throughput is relatively insensitive to the choice of thresholds while the link quality metrics such as BER and BLER depend heavily on the thresholds. The proposed algorithm described in this section maintains the quality metric of interest (either BLER or BER) around a desired value.

The proposed quality control algorithm is designed to satisfy the quality requirement in the steady state when the expected step-change in the thresholds is zero. The algorithm computes estimates of the MCS probabilities (P_n) and MCS error rates (p_n) for all MCS levels. Updates of the proposed algorithm are computed every time a packet is decoded and its CRC result is available. In the tth update instant, let the MCS level of the current packet be denoted by $m \in \{1, 2, \cdots, M\}$. MCS probability estimates can be computed using an averaging technique such as the following exponential averaging update. For each $n = 1, 2, ..., M$,

$$\hat{P}_n(t) = \begin{cases} \lambda \hat{P}_n(t-1) + (1-\lambda) & \text{if } n = m, \\ \lambda \hat{P}_n(t-1) & \text{otherwise,} \end{cases} \tag{7}$$

where the "forgetting factor" λ is a number between 0 and 1 (usually close to 1). An estimate of the error rate for the mth MCS level at update instant t, denoted by $\hat{p}_m(t)$, is also similarly computed for the MCS level of the received packet.

$$\hat{p}_m(t) = \begin{cases} \lambda \hat{p}_m(t-1) + (1-\lambda) & \text{if CRC check fails,} \\ \lambda \hat{p}_m(t-1) & \text{if CRC check succeeds.} \end{cases} \tag{8}$$

For $n \neq m$, the error rate estimates are kept unchanged: $\hat{p}_n(t) = \hat{p}_n(t-1)$. A desired value of the mth MCS error rate p_m, denoted by[1] p_m^d, is then computed that would meet the quality criterion if all other estimates were accurate.

If constant BLER (P_{BL}^{Target}) is the target criterion, then p_m^d is computed, using (3), as

$$p_m^d = \frac{1}{\hat{P}_m(t)} \left[P_{BL}^{Target} - \sum_{\substack{n=1 \\ n \neq m}}^{M} \hat{p}_n(t) \hat{P}_n(t) \right]. \tag{9}$$

If constant BER (P_B^{Target}) is the target criterion, then, from (5), the desired error rate is computed as

$$p_m^d = \frac{1}{R_m \hat{P}_m(t)} \left[P_B^{Target} \sum_{n=1}^{M} R_n \hat{P}_n(t) - \sum_{\substack{n=1 \\ n \neq m}}^{M} R_n \hat{p}_n(t) \hat{P}_n(t) \right]. \tag{10}$$

In a similar fashion to step-based control loops we define two step sizes for the adjustment of each threshold: the up-step Δ_m^+ and the down-step Δ_m^-, defined as the increment and decrement of the mth threshold, respectively. The up-step to down-step ratio for the mth threshold is then set to satisfy[2]

$$\frac{\Delta_m^+}{\Delta_m^-} = \frac{1 - p_m^d}{p_m^d}. \tag{11}$$

[1] Dependence of m and p_m^d on t is suppressed in notation.

[2] The reader familiar with quality control loops for power controlled dedicated channels, may notice the similar choices made in the Outer Loop Power Control (OLPC). One difference is that here, the step sizes and their ratios are adaptive.

One way to satisfy the above condition is to use

$$\Delta_m^+ = \delta(1 - p_m^d), \tag{12}$$
$$\Delta_m^- = \delta p_m^d, \tag{13}$$

where δ is a small positive constant number. Alternatively, one of Δ_m^+ and Δ_m^- can be held constant while the other is computed to satisfy (11).

If $m > 1$, then threshold θ_m is adjusted according to the following rule:

$$\theta_m(t) = \begin{cases} \theta_m(t-1) + \Delta_m^+ & \text{if CRC check fails,} \\ \theta_m(t-1) - \Delta_m^- & \text{if CRC check succeeds.} \end{cases} \tag{14}$$

As noted in Section 2, the first threshold θ_1 is fixed at negative infinity if transmission is mandatory in every packet interval. If there is no such constraint, then θ_1 is also updated using the above expression.

3.1 Hybrid ARQ (HARQ) Considerations

In packet communications, HARQ schemes are usually employed top facilitate retransmissions in case of CRC failures. Two choices in the quality criteria can be established in the presence of an HARQ scheme:

1. Pre-HARQ BER or BLER;
2. Post-HARQ residual BER or residual BLER.

The method described in Section 3 can be used directly if pre-HARQ criteria are targeted. Average number of retransmissions experienced by any bit is directly related to the pre-HARQ BER. Since the above method which updates for every CRC result controls the pre-HARQ BER, the same will also control the average delay experienced by the bits due to retransmissions.

If post-HARQ criteria are targeted, the above method can be used with a small modification in the updating instants. Threshold updates are performed not for every packet, but only when at least one of the following is true: (*i*) CRC check succeeds, or (*ii*) the number of retransmissions equals the maximum allowable number of retransmissions.[3] In other words, probability estimates $\hat{P}_n$ and $\hat{p}_n$, for all n, and thresholds θ_n are updated according to the above update rules only if the present transmission is the last transmission for the present packet.

4 QCL Performance

Performance of QCL is demonstrated in this section via simulation results with and without QCL under different antenna schemes. Simulations are performed with the HSDPA assumptions. In addition, the following are assumed.

- Single path Rayleigh fading channel (Case 0)
- Geometry = 6 dB

[3]The maximum number of retransmissions is set by higher layers and depends on the QoS requirements of the application.

- No MCS feedback delay
- 10/16 codes use 70% of base station power
- Uncorrelated transmit antennas when multiple antenna transmission is used
- Single receive antenna
- 5-element MCS table
- Ideal SINR estimate used as channel quality metric
- Error-free MCS feedback
- 4% feedback bit error rate for closed-loop antenna schemes.
- Simulations are run over 2000 radio frames (10000 TTI's)
- Target criterion is pre-HARQ BER for simulations with and without HARQ
- Target pre-HARQ BER is set in the QCL algorithm at 0.09.

Figures 5 through 5 show throughput and BER performance without HARQ. Figure 5 corresponds to a single transmit antenna, Figure 5 corresponds to Selection Transmit Diversity (STD) with two transmit antennas, Figure 5 corresponds to STTD encoded signaling with two transmit antennas, and Figure 5 corresponds to Closed-Loop Transmit Diversity (CLTD) with two transmit antennas and Mode-1 feedback. The plots clearly show successful quality control using QCL, while the quality metric without QCL quickly deteriorates beyond acceptable level with increasing mobility.

Figures 5 and 5 show the performance with HARQ. The target criterion is set to be pre-HARQ BER, since this controls the average bit delay caused by retransmissions. Figure 5 corresponds to single antenna transmission and Figure 5 corresponds to a 2×1 system with STTD. As expected, the pre-HARQ BER and average bit delay are maintained constant by QCL.

5 Conclusions

From the operational point of view schemes are needed that allow the control of the Quality of Service (QoS) criteria that the Medium Access Control (MAC) and/or Physical Layers deliver to the application under a wide variety of conditions. In this memo we presented a simple scheme to control BLER or BER metrics by mean of adjusting the MCS selection thresholds of link adaptation. The proposed algorithm is simple to implement and is shown to be capable of tightly controlling the quality metrics even in harsh mobility environments.

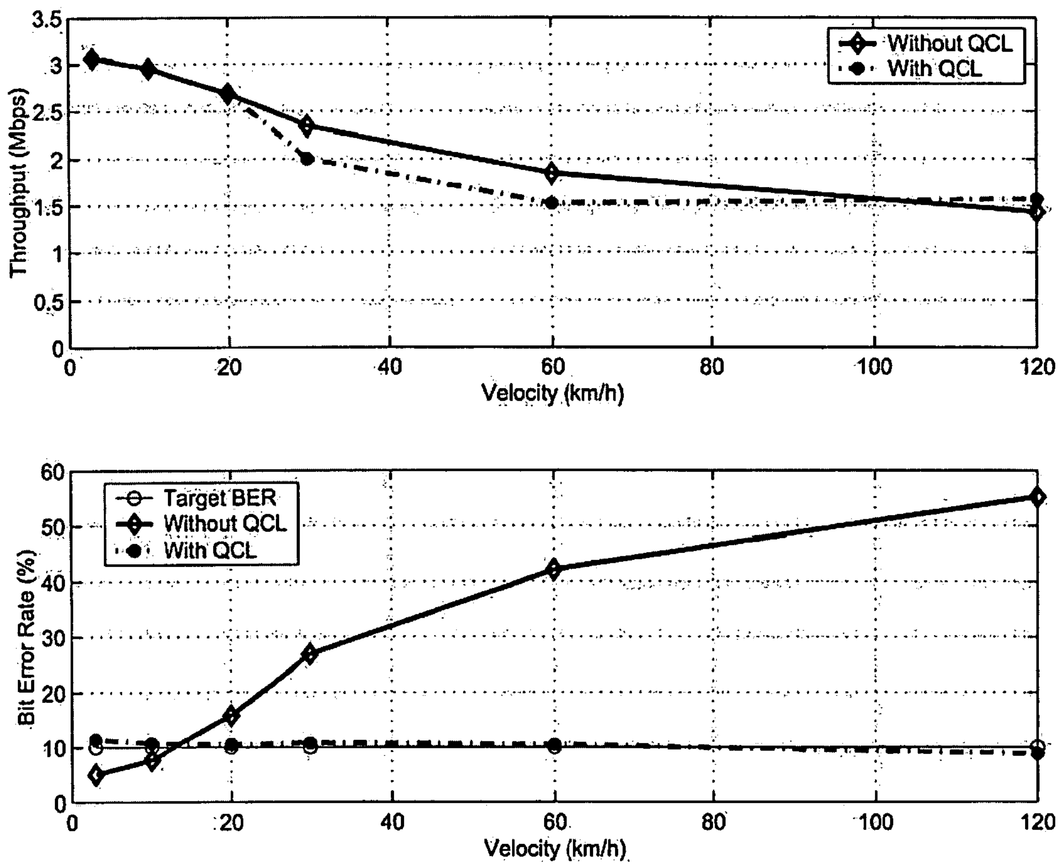

Figure 1: Performance and quality metrics of 1×1 system with no HARQ

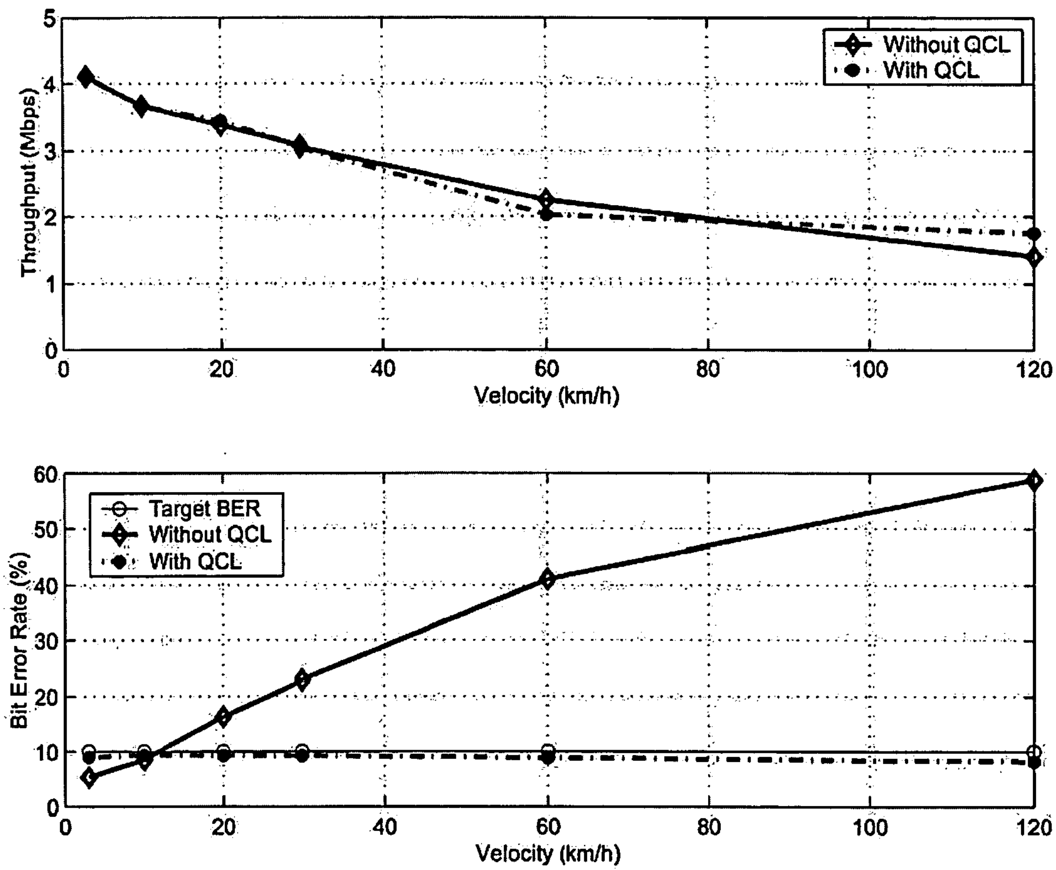

Figure 2: Performance and quality metrics of 2×1 system with Selection Transmit Diversity (STD), no HARQ

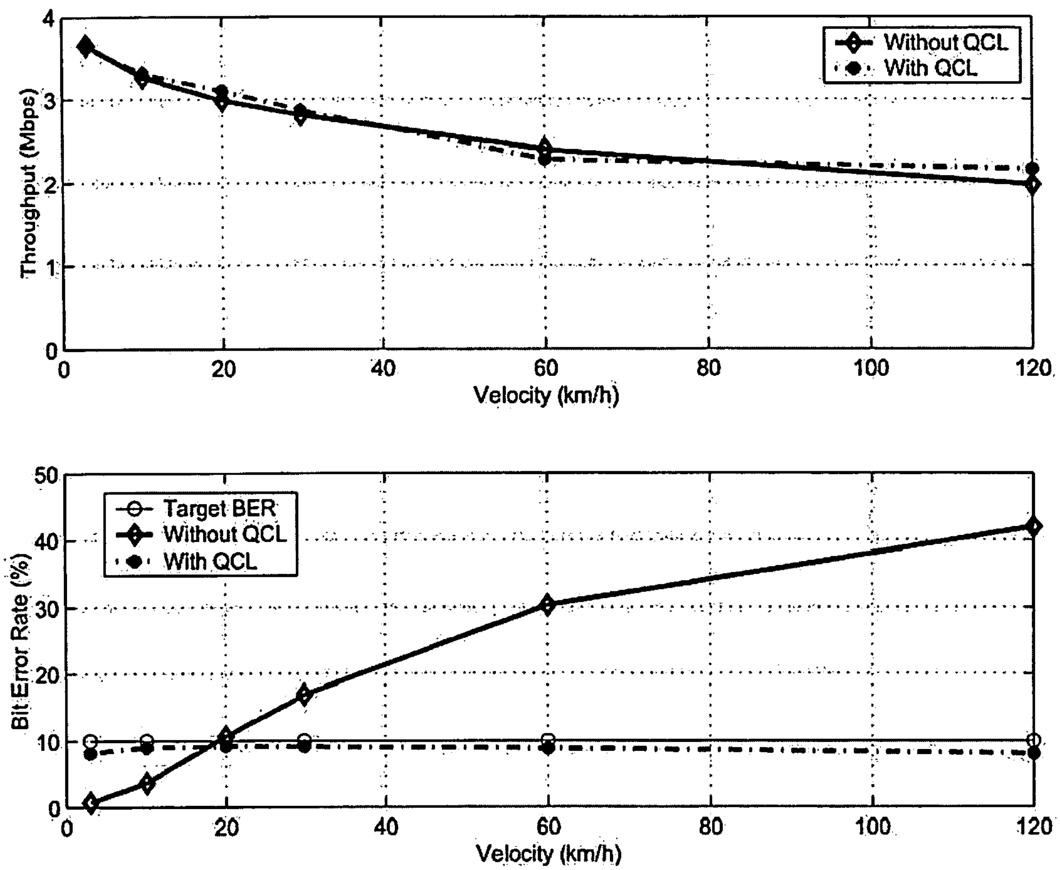

Figure 3: Performance and quality metrics of 2×1 system with Space-Time Transmit Diversity (STTD), no HARQ

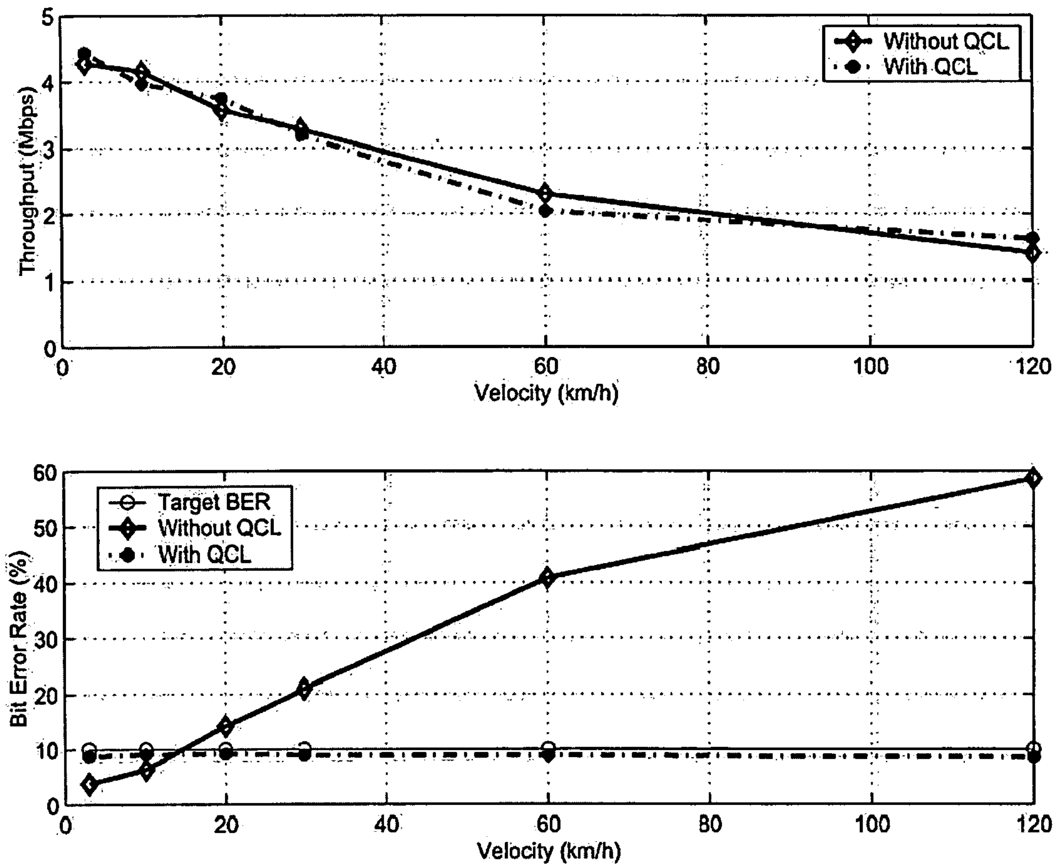

Figure 4: Performance and quality metrics of 2×1 system with Closed-Loop Transmit Diversity (CLTD), no HARQ

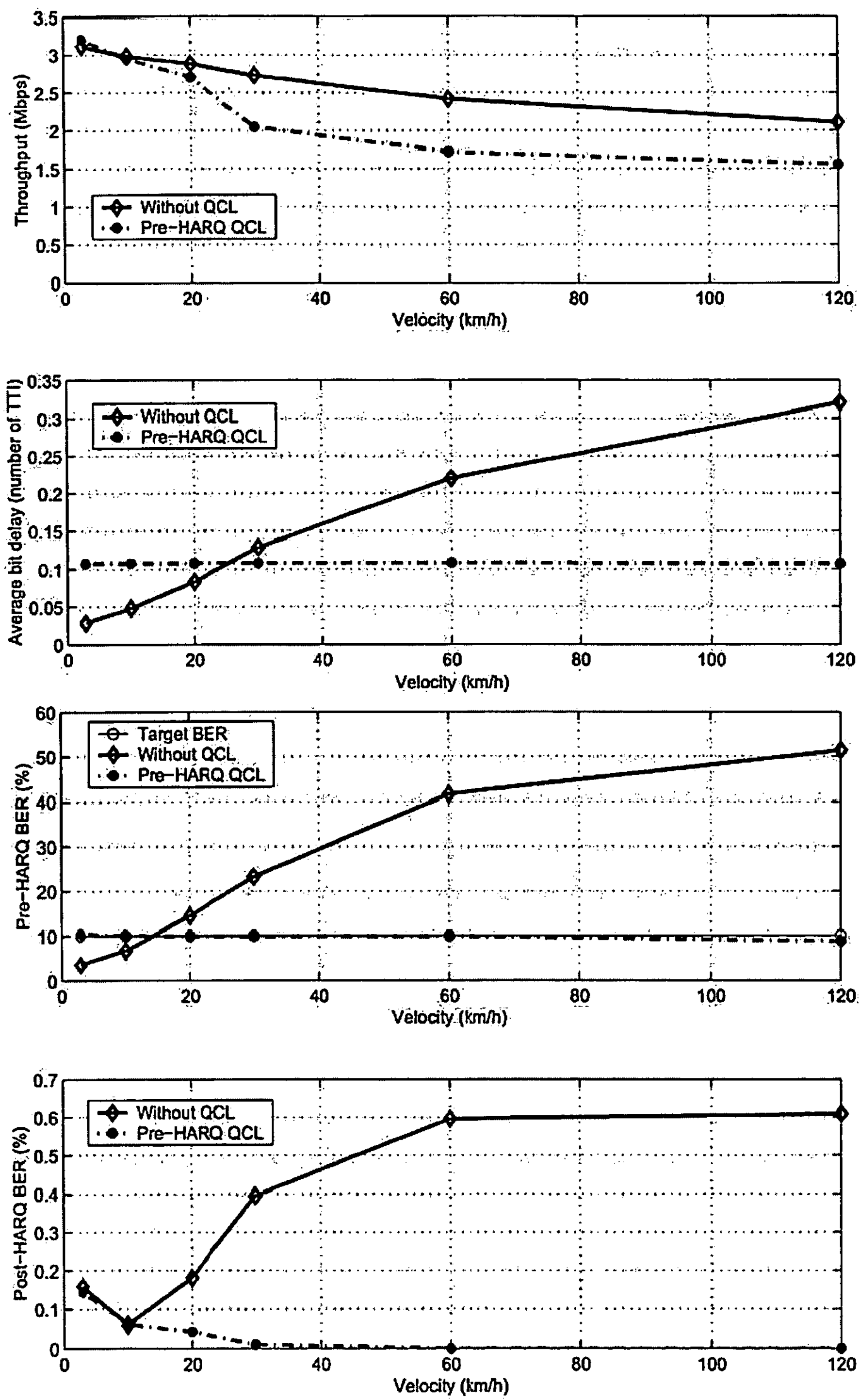

Figure 5: Performance and quality metrics of 1×1 system, with Chase combining HARQ

Sridhar Gollamudi

LC-00000-SG/PM/typ **Pantelis Monogioudis**

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References
Appendixes A and B

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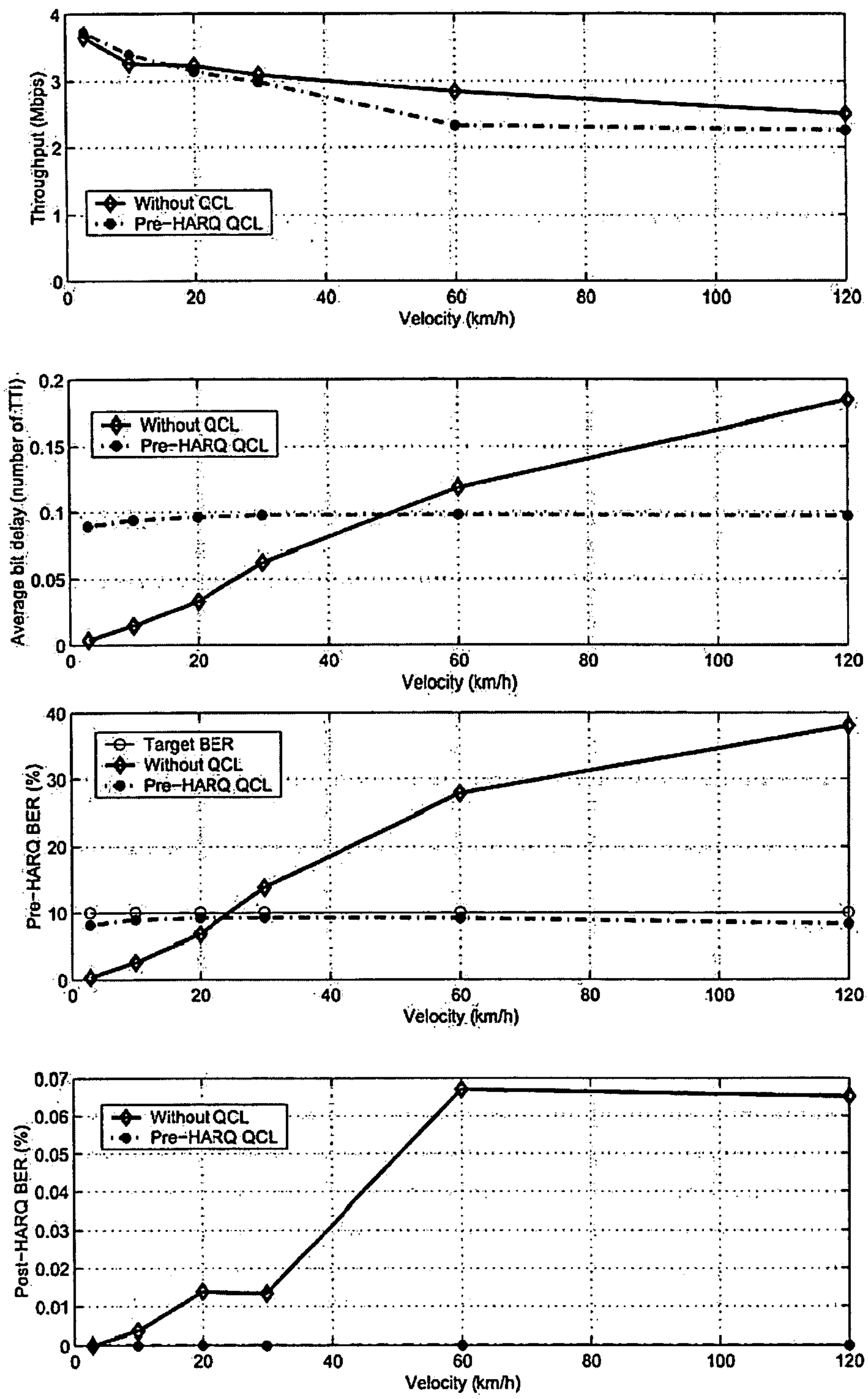

Figure 6: Performance and quality metrics of 2 × 1 system with Closed-Loop Transmit Diversity (CLTD), with Chase combining HARQ

References

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Authors	Electronic Address	Location	Phone	Company (if other than Lucent–BL)
Sridhar Gollamudi	gollamudi@lucent.com	LC 9N-Z00	9999	
Pantelis Monogioudis	monogiou@lucent.com	LC 9N-Z00	9999	

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Abstract

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Author Signatures

Sridhar Gollamudi	Pantelis Monogioudis	

Organizational Approvals

M. Y. Head, Head 00000	M. Y. Head, Head 00000	

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